

## **Acoustic Seaglider™ for Beaked Whale Detection**

### **Final Report**

Submitted to

Dr. Michael Weise  
Program Officer, Marine Mammals and Biology  
Office of Naval Research  
875 N. Randolph Street  
Arlington VA 22203

By

Neil M. Bogue  
Applied Physics Laboratory  
University of Washington  
Box 355640  
Seattle WA 98195-5640  
phone: (206) 221-7687 fax: (206) 543-6785 email: [bogue@apl.washington.edu](mailto:bogue@apl.washington.edu)

James C. Luby, Ph.D.  
Applied Physics Laboratory  
University of Washington  
Box 355640  
Seattle WA 98195-5640  
phone: (206) 543-6854 fax: (206) 543-6785 email: [jcl@apl.washington.edu](mailto:jcl@apl.washington.edu)

30 September 2011

Award Number: N00014-08-1-0309  
<http://www.apl.washington.edu>

## **ABSTRACT**

This is the final report on the Office of Naval Research (ONR)-sponsored program entitled “Acoustic Seaglider™ for Beaked Whale Detection”. This research at the Applied Physics Laboratory of the University of Washington (APL-UW) was part of the ONR Passive Autonomous Acoustic Monitoring (PAAM) of marine mammals program. Research was focused on development and operation of a passive acoustic system for the buoyancy-driven autonomous underwater vehicle Seaglider, capable of autonomous detection and classification of beaked whales. The Seaglider/PAAM system consists of a single omnidirectional hydrophone, an APL-UW designed and built electronics board, and operating software. Colleagues D. Mellinger and H. Klinck at Oregon State University developed detectors and provided scientific guidance. Four major field programs were executed, including deployments at the Navy ranges AUTEC and SCORE. Beaked whale detections ranges of up to four km were noted at AUTEC. Further development of hardware and software continues under a follow-on award from ONR.

## **INTRODUCTION**

This is the final report on research conducted with support from the Office of Naval Research (ONR), under award number N00014-08-1-0309, entitled Acoustic Seaglider™ for Beaked Whale Detection. The award was part of ONR’s Passive Autonomous Acoustic Monitoring (PAAM) marine mammal program. The PAAM program was originated within ONR Code 322 Physical Oceanography by CAPT Douglas Marble, USN, Ph.D., and later managed by Marine Mammals and Biology program officer Dr. Michael Weise.

The research was performed between 01JAN2008 and 30JUN2011 under the direction of Principal Investigators Mr. Neil M. Bogue and Dr. James C. Luby of the Electronic and Photonic Systems Department of the Applied Physics Laboratory at the University of Washington.

This report will loosely follow the format for ONR Annual Reports.

## **LONG-TERM GOALS**

The research described in this report was performed by a technical group at the Applied Physics Laboratory of the University of Washington (APL-UW) that is dedicated to the use of autonomous underwater vehicles, and buoyancy-driven gliders in particular, in support of Navy missions. The group generally uses the Seaglider™, developed at the University of Washington (Eriksen, *et al.* [2001]), and develops or adapts instruments and glider behavior to support specific Navy mission requirements. This group is informally called the Applied Seaglider Group, whose acronym, ASG, is also used to describe the Applied Seaglider itself.

This report describes the group’s efforts as part of ONR’s Passive Autonomous Acoustic Monitoring (PAAM) marine mammal program. The original long-term goals of the PAAM program, as formulated by CAPT Marble, were as follows.

- Perform persistent and autonomous passive acoustic monitoring of a 500-1000 square nautical

mile Navy exercise area for presence of marine mammals.

- Monitor for three weeks prior to, three weeks during, and three weeks after a typical exercise.
- Detect, classify and localize (DCL) vocalizing marine mammals.
- Provide actionable information in a timely manner to the officer in tactical command in support of marine mammal mitigation efforts.

By the end of the program, the long-term goals of the PAAM program had moved away from mitigation to concentrate on the DCL mission in support of monitoring marine mammals, particularly in active Navy operating areas.

## OBJECTIVES

The primary objective was to build a passive acoustic detection and recording system for the Applied Seaglider, with particular attention to the automated detection and classification of beaked whale vocalizations, and to quantify the system's performance with respect to the goals of the ONR PAAM program outlined above.

## APPROACH

The efficacy of the autonomous underwater glider Seaglider for passive acoustic observations of marine mammals was first demonstrated in Monterey Bay, CA, in 2006 (Moore, *et al.*, [2007]). The original Seaglider Acoustic Recording System (ARS) was designed to operate in the 5Hz to 30kHz band, and successfully recorded vocalizations of blue, humpback, and sperm whales, along with various whistles and clicks typical of odontocetes.

The research reported here focused on development and operation of a system capable of autonomous detection and classification of beaked whales, animals that emit high frequency, directional, predatory echolocation clicks at depths greater than a few hundred meters (Zimmer, *et al.*, [2005]). This choice was motivated by several factors. First, widely publicized strandings of beaked whales have occurred in proximity to the U.S. Navy's use of tactical mid-frequency active sonar. Evans and England [2001] described a particularly prominent incident in the Northeast and Northwest Providence Channels, Bahamas, in March 2000. D'Spain *et al.* [2006] discussed several of these strandings in more detail, and provided a description of the properties of the underwater sound field associated with each incident. Second, beaked whales vocalize at depths greater than 200m and use frequencies above 25kHz, as described by Zimmer *et al.* [2008], Johnson *et al.* [2004], and Zimmer *et al.* [2005]. The described characteristics are a good match with the Seaglider's depth range and physical dimensions, in that large acoustic apertures are not required, and that Seaglider's maximum depth rating of 1000m is similar to the foraging depths of beaked whales. Finally, due to the relatively high frequencies and narrow beam pattern of the beaked whale echolocation clicks, detection ranges were expected to be of order a few kilometers. This meant that detection was also effectively localization, with respect to the horizontal scale of 500-1000 square nautical mile Navy operating area.

Our approach was as follows.

- Design and build a new acoustic detection and recording system with sufficient sampling rates, processing power, and storage capacity to enable Seaglider as an effective platform for beaked whale detection and recording.
- Collaborate with Drs. David Mellinger and Holger Klinck at Oregon State University (OSU) on beaked whale detection and classification algorithms.
- Conduct a series of bench and in-water tests to characterize system performance.
- Deploy locally in the presence of killer whales (*Orcinus orca*) as a proxy for beaked whales.
- Deploy off Kona (west) coast of island of Hawai'i on beaked whale survey missions.
- Deploy on instrumented Navy ranges (AUTC and SCORE) in the presence of beaked whales to quantify detection performance.

Key participants at APL-UW, in addition to the Principal Investigators listed above, were Bill Jump (hardware and system design engineer), Geoff Shilling (software engineer), Trina Litchendorf (ASG Lab), Angie Wood (ASG Lab), and Paul St. Laurent (ASG Lab). A UW undergraduate, Mariah Gentry, provided essential data processing and analysis. Drs. David Mellinger and Holger Klinck at OSU have provided detection algorithms and performed analysis of detector performance. Ms. Karolin Klinck of OSU reviewed acoustic recordings for presence of marine mammal vocalizations.

## WORK COMPLETED

This award funded the design, fabrication and testing of a new acoustic detection and recording system for Seaglider. The system consists of a single omnidirectional HTI-99-HF hydrophone and a custom designed and built electronics board. The hydrophone is mounted external to the Seaglider aft fairing, at the dorsal centerline as shown in Figure 1, and cabled to the PAAM electronics board via a connector on the Seaglider pressure hull end cap.

We designed and built a new electronics board for Seaglider to handle data acquisition and signal processing in support of the beaked whale detection mission. The design constraints and performance requirements of this board were severe. It had to physically fit in the Seaglider electronics section, which required a footprint of 21.5cm x 8.3cm x 2.5cm. The board needed to digitize the input analog hydrophone signals at up to 250k samples per second, in order to fully resolve beaked whale echolocation clicks. It also had to contain enough processing power and flexibility to run on-the-fly detectors, on-board classifiers, and manage storage of the raw acoustic records. Finally, it had to run at extremely low power levels, typically less than 1W, to achieve the PAAM program's persistence goals.

The Seaglider/PAAM board fits in the electronics section of Seaglider, below the main electronics board and above the 10V battery pack. It communicates with the main Seaglider computer via an RS-232 serial line. Pictures of the Seaglider/PAAM board are shown in Figures 2 and 3.

The Seaglider/PAAM board's main attributes are given below.

- Four channels, 16-bit digitization
- 250kHz maximum aggregate sample rate
- Plug-in passive filters (TTE)
- Optional active filters (jumper selectable)
- ARM-9 processor (LPC-3180) running Linux, 13-208MHz clock

- Power consumption (typical) 840mW @ 208MHz
- Data storage (maximum, current operational version)
  - 2x32GB SD cards + 2x128GB USB memory = 320GB

Software was written to buffer the digitized data stream, record data to SD cards, implement on-the-fly time-domain click detectors (Klinck and Mellinger, [2011]), and control the PAAM system through the Seaglider Iridium™ telemetry. This required completion of a substantial amount of low-level software: CPLD code, SPI bus drivers, SD card drivers, and Linux kernel modifications, in addition to modifications to the existing Seaglider and basestation code. A major focus of the software effort was performance – all processes had to be able to keep up with the fast sample rates ( $\geq 192$ k samples per second) demanded by the frequency content of beaked whale clicks.

The PAAM board is controlled via the Seaglider worldwide Iridium telemetry link. Various aspects of the board's configuration are under parameter control by the pilot; the board itself may be turned on and off by the Seaglider in response to the pilot's settings. For example, a pilot may choose to only activate the PAAM board below a specified depth, or only in accordance with a specified time schedule, or only when the Seaglider itself is quiet (no motors are active). Detection reports and statistics, power spectra, and time series snippets can all be transmitted via Iridium for inspection at a command center.

Full suites of performance characterization tests were done. The sequence began with functional board-level bench tests and extensive runs on a Seaglider test bed at APL-UW. Simple characterization tests of the PAAM system were conducted at the APL-UW dock, using a calibrated source. These tests validated the analog signal path and calculated gains for the PAAM system. Additional system characterization tests were used to determine an approximate detection range for beaked whale clicks (at frequency and source levels described in Zimmer *et al.* [2008] and consistent with Johnson *et al.* [2004] and Zimmer *et al.* [2005]).

On 4SEP2009, Seaglider SG022 was deployed from Western Washington University's R/V ZOEI in the eastern part of Juan de Fuca and Haro Straits off San Juan and Lopez Islands. Conditions were calm, visibility was excellent, and portions of all three pods of southern resident killer whales (*Orcinus orca*) were present at various times.

SG022 completed five dives in water depths between 60m to 120m. SG022 was positioned at the start of each dive at ranges to the killer whale pods of between 0.8km and 3.5km. The PAAM board was configured to run the ERMA click detector (Klinck and Mellinger, [2011], configured for *O. orca* clicks), and also to record the complete acoustic time series during each dive. A total of 3.7 GB of acoustic data was recorded, representing 168 minutes of recording.

Four major field deployments to detect and record beaked whale vocalizations were completed on this program, as shown in Table 1 below: two off the west coast of the island of Hawai'i and one each at the U.S. Navy's AUTEC and SCORE ranges.

Deployment	Seaglider	Dates	Number of Dives (1km)	Hours of Recording <sup>1</sup>	GB of Recording <sup>2</sup>
Haro Strait	SG022	4SEP2009	5 (0)	2.8	3.7
Kona I	SG022	27OCT2009-17NOV2009	116 (102)	170.2	141.5
Kona II	SG022	16MAR2010-26MAR2010	61 (42)	101.8	84.6
	SG023		94 (36)	107.1	89.0
AUTC	SG178	7JUN2010-11JUN2010	35 (12)	58.5	48.6
	SG179		27 (12)	71.7	59.6
SCORE	SG178	4JAN2011-7JAN2011	30 (19)	56.2	46.7
	SG179		30 (19)	53.5	44.5
Total		56 days	398 (223)	621.8	518.2

<sup>1</sup>Duty-cycle governed by detect\_below parameter

<sup>2</sup>Sample rate = 194162 samples per second, 16-bit A/D conversion, FLAC encoding (ratio  $\approx$  0.6)

**Table 1.** Summary of field deployments on Seaglider/PAAM program.

## RESULTS

The Kona I and Kona II deployments were guided by Baird *et al.* [2006] and McSweeney *et al.* [2007].

Seaglider SG022's surfacing positions during the KONA I deployment are shown in Figure 4. The intent was to keep SG022 close to the 1500m isobath, the approximate midpoint of the habitats favored by Blainville's (*Mesoplodon densirostris*) and Cuvier's (*Ziphius cavirostris*) beaked whales (Baird

[2009], private communication). Seaglider SG022 executed repeated dives to 1000m; the PAAM board was set to detect and record below 500m.

The ERMA click detector (Klinck and Mellinger [2011]) was effective at distinguishing click trains from other signals. It was not as proficient at separating naturally-produced sounds (beaked whale clicks) from man-made sounds (fathometers and fish finders). Detection statistics were skewed by the presence of these man-made sounds. Improvement in this aspect of the detector was a major motivation for Kona II.

The beaked-whale interclick interval (ICI) was a useful diagnostic, however. Cases where the post-dive report indicated a large number of energetic clicks with a high percentage within the typical beaked whale ICI range were examined manually after recovery of the Seaglider. A typical result is shown in Figure 5.

Results such as presented in Figure 5 demonstrated that the Seaglider/PAAM system could successfully detect the presence of beaked whales, record their vocalizations in high enough fidelity to provide confidence in the detections, and report these detections in close to real time via Iridium satellite telephone.

Kona I demonstrated the feasibility of a large part of the original PAAM program requirements: passive autonomous detection (and hence, since detection ranges are order a few kilometers, rough localization) of beaked whales, persistence of nine weeks, and near real-time notification.

Complete sets of acoustic time series from Kona I and Kona II were sent to Drs. Mellinger and Klinck at OSU for analysis of detector performance. Results from Kona I were reported by Dr. H. Klinck at the Seattle meeting of the Acoustical Society of America in May, 2011 (Klink, *et al.*, [2011]).

The Kona II deployment of sg022 and sg023 had two goals: implement an improved version of the ERMA detector to better discriminate between beaked whale clicks and man-made sounds, and to deploy two Seagliders to enhance detection opportunities.

Seagliders SG022 and SG023 were deployed out of Kailua-Kona on 16MAR2010. Unfortunately, SG023 developed a problem with its roll mechanism on 23MAR2010, and lost heading control when it was about 40nm offshore. SG022 continued to operate normally on its inshore patrol mission, as in Kona I. Both Seagliders were recovered on 25MAR2010.

The Kona II deployment was long enough to verify the performance of the enhanced detector provided by Drs. Mellinger and Klinck of OSU. This detector was focussed more tightly on Blainville's beaked whale (*Mesoplodon densirostris*).

The third deployment of FY2010 was of Seagliders SG178 and SG179 at the Atlantic Undersea Test and Evaluation Center (AUTC), between 6JUN2010 and 11JUN2010. The Seagliders were deployed in AUTC Weapons Range North. Personnel from D. Moretti's group at NUWC/Newport ran the M3R (Marine Mammal Monitoring on Navy Ranges) software on the AUTC hydrophone acoustic feeds for the duration of the deployment.

Tracks of the Seagliders in the AUTC deployment are shown in Figure 6. SG178 was commanded to stay in the vicinity of range hydrophone H4, at the center of the W1 high-resolution array, a known

“hot spot” for beaked whales. SG179 was commanded on repeated east-west transects across AUTECH Weapons Range North; the western terminus of the transect was the area above range hydrophone H4.

A summary of the Seaglider click detections during the AUTECH deployment is given in Table 2 below. Note that these data summarize individual click detections, not individual encounters with animals, either singly or in groups.

Date June 2010 178/179	SG178					SG179				
	Dive	Dive Depth (m)	Detect Below (m)	Click Detect -ions	Detect -ions in ICI	Dive	Dive Depth (m)	Detect Below (m)	Click Detect -ions	Detect -ions in ICI
7JUN	1	49	5	191	19	1	51	5	8	0
7JUN	2	94	5	17	0	2	95	100	5	0
7JUN	3	183	5	13	3	3	458	100	8	1
7JUN	4	454	100	24	0	4	667	100	47	13
7/8JUN	5	663	100	129	5	5	916	300	23	1
8JUN	6	907	100	1763	331	6	912	300	9746	1996
8JUN	7	910	300	8511	1492	7	911	300	891	409
8JUN	8	913	300	2	0	8	915	300	965	474
8JUN	9	907	300	2	0	9	957	300	372	221
8/9JUN	10	902	300	4	0	10	1012	300	79	66
8/9JUN	11	904	300	70	24	11	979	150	1501	739
8/9JUN	12	909	300	3	0	12	959	150	64	17
8/9JUN	13	908	300	4	0	13	985	150	11	0
9/10JUN	14	1005	300	107	53	14	971	150	0	0
9/10JUN	15	992	300	718	465	15	1001	150		
9/10JUN	16	990	150	0	0	16	1002	150	13	5
9/10JUN	17	993	150	672	458	17	998	150	14	6
9/10JUN	18	991	150	1946	1258	18	1008	150	8	0
9/11JUN	19	671	150	412	106	19	1001	150	12	3
10/11JUN	20	994	150	0	0	20	998	150	43	0
10/11JUN	21	993	150	3	0	21	677	150	16	1
10/11JUN	22	995	150	14	2	22	675	50	3	1
10/11JUN	23	995	150	2634	1731	23	184	10	3	0
10/11JUN	24	995	150			24	184	10	0	0
10/11JUN	25	996	150	104	68	25	51	10	2	1
10/11JUN	26	991	150	27	13	26	53	10	93	65
11JUN	27	991	150	3	0	27	123	10	7	0

**Table 2.** AUTECH PAAM Seaglider beaked whale detection summary.

Drs. Mellinger and Klinck at OSU, along with K. Klinck, analyzed the June, 2010 AUTECH recordings. They have presented their results in detail (Klinck, *et al.*, [2011]), but a couple results are worth mentioning here, as they provide some system-level performance characterizations.

The performance of the Seaglider ERMA detector was compared with the M3R detections coincident in space and time. Results are shown in Table 3 below.

<b>Glider operation</b>	<b>BW encounters</b>	<b>ERMA detections</b>	<b>M3R detections</b>	<b>ERMA false detections</b>	<b>M3R false detections</b>
stationary	11	11	10	2	0
transect	12	12	8	1	0
<b>Total</b>	<b>23</b>	<b>23 (100%)</b>	<b>18 (78%)</b>	<b>3</b>	<b>0</b>

**Table 3.** Detector comparison from AUTECH, June 2010 deployment of two Seagliders, courtesy of Drs. D. Mellinger and H. Klinck, OSU.

The ERMA detector did not miss any of the Seaglider's beaked whale encounters, but had a few false detections. The M3R system missed a few beaked whale encounters, but had no false detections. This may be because the M3R system is tuned as a ground-truth system, with a premium on low false-alarm rate, while the ERMA detector was tuned to not miss detections.

The Seaglider/PAAM system detection range was approximated by measuring the horizontal distance between a Seaglider when it had a beaked whale detection, and the nearest AUTECH hydrophone with a beaked whale detection within five minutes. Note that ranges calculated in this way are not between the Seaglider and the beaked whale. Results of this analysis are presented in Figure 7. Detection distances of greater than six kilometers are probably coincidence, since the ocean's absorption of acoustic energy at the frequencies of the beaked whale clicks precludes detections at greater than about six kilometers. The results from the station-keeping Seaglider (SG178) are probably more reliable, since there were longer beaked whale encounters, and the horizontal spacing of the W1 hydrophone array means there were more hydrophones near SG178 at all times.

These results suggest that the Seaglider/PAAM system has a detection range for on-axis beaked whale clicks of up to 4km in the AUTECH acoustic environment.

The final field deployment on this project was at the Navy's SCORE range between 4JAN2011 and 7JAN2011. Surfacing positions for the two Seagliders deployed on the SCORE range on 4JAN2011 are shown in Figure 8. Both Seagliders were launched at the southeast end of a track line suggested by D. Moretti of NUWC-Newport, based on his experience operating the Navy's Marine Mammal Monitoring on Ranges (M3R) system on the SCORE instrumented range. No beaked whale detections were made by the Seagliders during the three-day deployment. The M3R system also showed no beaked whale detections on hydrophones within acoustic range of the Seagliders in the same time period. So while it was perhaps bad luck that the Seagliders did not detect any beaked whales on this deployment, it is encouraging that the negative result is consistent with the M3R results in the same area at the same time.

Vocalizations of other species of marine mammals were recorded during the deployment, however. An example is shown in Figure 9, a Long-Term Spectral Average from SG 178's dive 12 on 6JAN2011. This result is included to demonstrate the utility of the Seaglider/PAAM system to record and resolve a variety of marine mammal vocalizations over a broad frequency band.

Finally, a note on persistence. Under the following assumptions, the persistence of the Seaglider/PAAM system is given in Table 4 below.

- 10V Capacity 3.7MJ, 24V Capacity 12.3MJ, both available to PAAM
- 9x64GB SD cards, 2x256GB USB sticks = 1088GB total storage
- 1000m dives, 4.75hrs, normal dive profiles (speed) and motor moves
- 194162 samples/s x 2 bytes/sample = 388324 bytes/s

Detect_below depth	5m	500m
10V per dive	18.4kJ	17.6kJ
24V per dive	66.5kJ	63.9kJ
Number of dives	386	403
Number of days	77	81
Storage per dive	3.74GB	1.83GB
Number of dives (to 90%)	262	535
Number of days	52	107

**Table 4.** Seaglider/PAAM persistence in two 1000m dive sampling duty-cycles: nearly always on (detect below 5m) and on about half the time (detect below 500m). The gray shaded areas are energy constraints; the unshaded areas are data storage constraints. The red numbers are the limits, in days.

The results are that under the assumptions given above, in a nearly always on configuration, the present Seaglider/PAAM system can operate for just over seven weeks. In a 50% duty-cycle configuration, the system can operate for over eleven weeks. Total mission time could be longer if the acoustic recording/detection system was turned off during transits.

## IMPACT/APPLICATIONS

The Seaglider/PAAM detection and recording system has achieved an initial operational capability. It has shown to be an effective tool for detecting beaked whale echolocation clicks, and relaying those detections ashore, with a reasonable amount of supporting data, in near real time. The Seaglider/PAAM system can be used in a variety of ways: as a bell-ringer detection system, as a monitoring system, and as a survey tool. Its persistence and ability to make long transits to a survey area may be useful in remote operating areas.

The Seaglider/PAAM system has the frequency range, computational power and flexibility, and persistence to be capable of a wide range of passive acoustic detection and recording missions. It is especially suitable for higher-frequency applications, where hydrophones can be small and large acoustic aperture is not required. The multi-channel electronics and sophisticated computational capability make integrating lower-frequency systems feasible.

## **RELATED PROJECTS**

We have a follow-on award to this project whose goals are to fully implement a beaked whale click classifier (Roch, *et al.* [2011]), enhancements to the PAAM board's data storage and management capacity, and to investigate multiple hydrophone installations to fully exploit the board's multi-channel capability. This project will also carry out a fleet-relevance or utility demonstration in FY2012.

Dr. David Mellinger at OSU is directly funded by ONR under the PAAM program to provide beaked whale detection and classification algorithms.

There are many related projects to use passive acoustics to detect, classify, and monitor marine mammals; some are funded as part of ONR's broader PAAM program, some are supported elsewhere.

## **TRANSITIONS**

We plan to transition the PAAM board to a private manufacturer, consistent with all export control regulations and requirements, so that the board could be made available as an add-on kit to current or future owners and operators of Seagliders. This transition will begin as the final configuration of the board is determined during the course of the follow-on project now underway.

## **PUBLICATIONS**

The following publications are connected with this program. Additionally, a publication describing the PAAM/Seaglider hardware is in preparation. We intend to submit that paper to the IEEE J. Oceanic Engineering.

Klinck, H., and Mellinger, D. K. [2011], "The energy ratio mapping algorithm: A tool to improve the energy-based detection of odontocete echolocation clicks", J. Acoust. Soc. Am., **129**(4), 1807-1812.

Roch, M. A., Klinck, H., Baumann-Pickering, S., Mellinger, D. K., Qui, S., Soldevilla, M. S., and Hildebrand, J. A. [2011]. "Classification of echolocation clicks from odontocetes in the Southern California Bight", J. Acoustic. Soc. Am., **129**(1), 467-475.

## PRESENTATIONS

Klinck, H., Mellinger, D. K., Roch, M. A., Klinck, K., Bogue, N. M., Luby, J. C., Jump, W. A., Pyle, J. M., Shilling, G. B., Litchendorf, T., and Wood, A. S. [2011]. "Passive-acoustic monitoring of odontocetes using a Seaglider: First results of a field test in Hawaiian waters", Presented at Seattle meeting of Acoust. Soc. Am, May 2011.

## REFERENCES

Baird, R. W., Webster, D. L., McSweeney, D. J., Ligon, A. D., Schorr, G. S., and Barlow, J. [2006]. "Diving behaviour of Cuvier's (*Ziphius cavirostris*) and Blainville's (*Mesoplodon densirostris*) beaked whales in Hawai'i", Can. J. Zool. **84**, 1120-1128.

D'Spain, G. L., D'Amico, A., and Fromm, D. M. [2006]. "Properties of the underwater sound fields during some well documented beaked whale mass stranding events", J. Cetacean Res. Manage., **7**(3), 223-228.

Eriksen, C. C., Osse, T. J., Light, R. D., Wen, T., Lehman, T. W., Sabin, P. L., Ballard, J. W., and Chiodi, A. M. [2001], "Seaglider: A Long-Range Autonomous Underwater Vehicle for Oceanographic Research", IEEE J. Oc. Eng., **26**(4), 424-436.

Evans, D.L. and England, G.R. [2001]. *Joint Interim Report Bahamas Marine Mammal Stranding Event 15-16 March 2000*. Department of the Navy and Department of Commerce (NOAA).

Johnson, M., Madsen, P. T., Zimmer, W. M. X., Aguilar de Soto, N., and Tyack, P. L. [2004]. "Beaked whales echolocate on prey", Proc. R. Soc. London, Ser. B **271**, S383-S386.

Klinck, H., and Mellinger, D. K. [2011], "The energy ratio mapping algorithm: A tool to improve the energy-based detection of odontocete echolocation clicks", J. Acoust. Soc. Am., **129**(4), 1807-1812.

Klinck, H., Mellinger, D. K., Roch, M. A., Klinck, K., Bogue, N. M., Luby, J. C., Jump, W. A., Pyle, J. M., Shilling, G. B., Litchendorf, T., and Wood, A. S. [2011]. "Passive-acoustic monitoring of odontocetes using a Seaglider: First results of a field test in Hawaiian waters", Presented at Seattle meeting of Acoust. Soc. Am, May 2011.

McSweeney, D. J., Baird, R. W., and Mahaffy, S. D. [2007]. "Site fidelity, associations, and movements of Cuvier's (*Ziphius cavirostris*) and Blainville's (*Mesoplodon densirostris*) beaked whales off the island of Hawai'i", Marine Mammal Science, **23**(3), 666-687.

Moore, S. E., Howe, B. M., Stafford, K. M., and Boyd, M. L. [2007], "Including Whale Call Detection in Standard Ocean Measurements: Application of Acoustic Seagliders", Marine Technology Society Journal, **41**(4), 53-57.

Roch, M. A., Klinck, H., Baumann-Pickering, S., Mellinger, D. K., Qui, S., Soldevilla, M. S., and Hildebrand, J. A. [2011]. "Classification of echolocation clicks from odontocetes in the Southern California Bight", J. Acoustic. Soc. Am., **129**(1), 467-475.

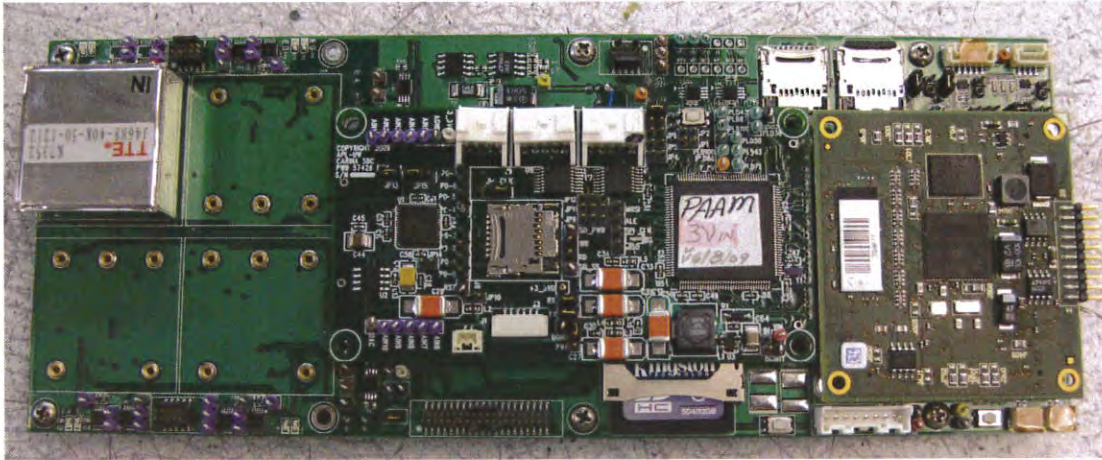
Zimmer, W. M. X., Harwood, J., Tyack, P. L., Johnson, M. P., and Madsen, P. T. [2008]. "Passive acoustic detection of deep-diving beaked whales", J. Acoust. Soc., Am, **124**, 2823-2832.

Zimmer, W. M. X., Johnson, M. P., Madsen, P. T., and Tyack P. L. [2005]. "Echolocation clicks of free-ranging Cuvier's beaked whales (*Ziphius cavirostris*)", J. Acoust. Soc. Am., **117**, 3919-3927.

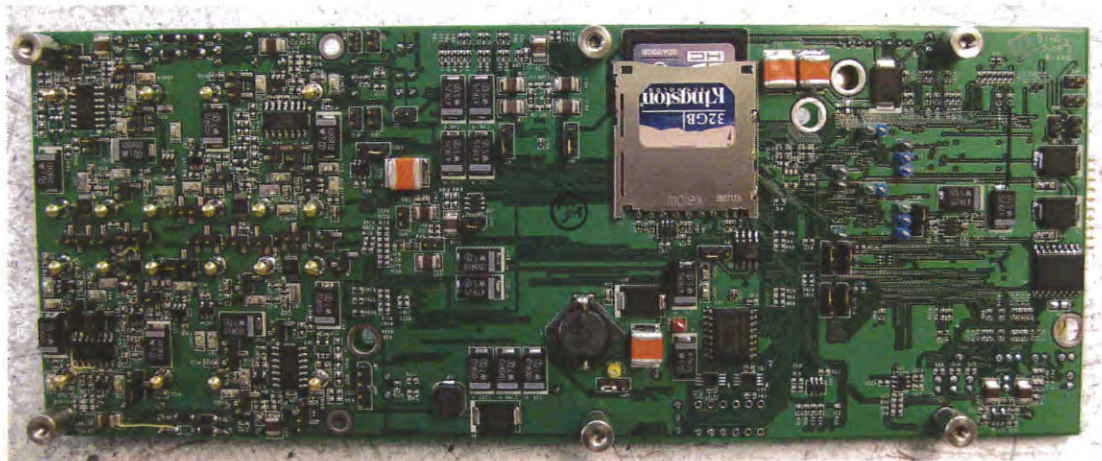
## FIGURES



**Figure 1.** Seaglider S/N 022 (SG022) on deck prior to launch on initial test mission in presence of killer whales (*Orcinus orca*) in the eastern Strait of Juan de Fuca, WA, on 4SEP2009. Note the single HTI-99-HF hydrophone on the dorsal centerline forward of the vertical stabilizer.



**Figure 2.** Seaglider/PAAM Rev. A electronics board, top view. The board has four analog channels; one analog filter (of four possible) is installed in upper-left corner of board. The daughter board in the middle is the ADuC845 microcontroller card. The daughter board on the right is the LPC3180 ARM9 CPU (with FPU), running Linux. Note the SD card slot at lower edge of board.

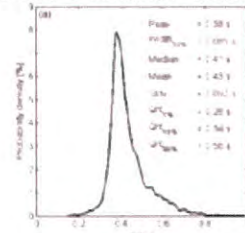


**Figure 3.** Seaglider/PAAM Rev. A electronics board, bottom view. Note the second SD card slot.



**Figure 4.** Seaglider SG022 surfacing positions off the Kona coast of the island of Hawai'i, 27OCT2009 – 17NOV2009. SG022 operated between a series of waypoints along the 1500m isobath, and dove to a depth of 1000m.

## Cuvier's beaked whale (*Ziphius cavirostris*)



Zimmer, W. M. X., Johnson, M. P., Madsen, P. T., and P. L. Tyack. 2005. Echolocation clicks of free-ranging Cuvier's beaked whales (*Ziphius cavirostris*). J. Acoust. Soc. Am. 117 (6): 3919-3927

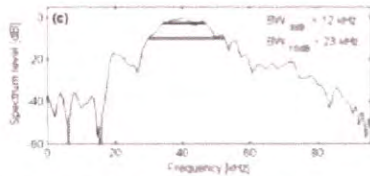
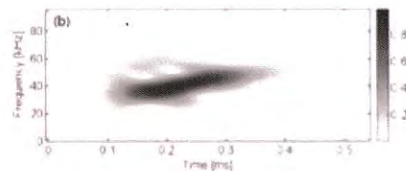
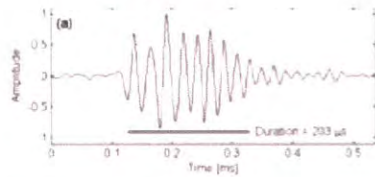
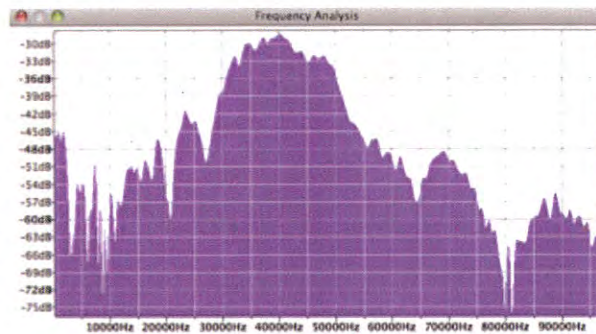
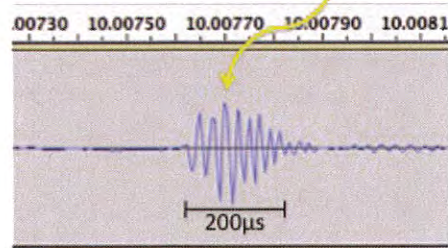
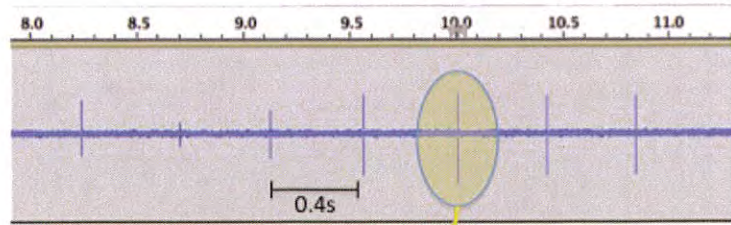
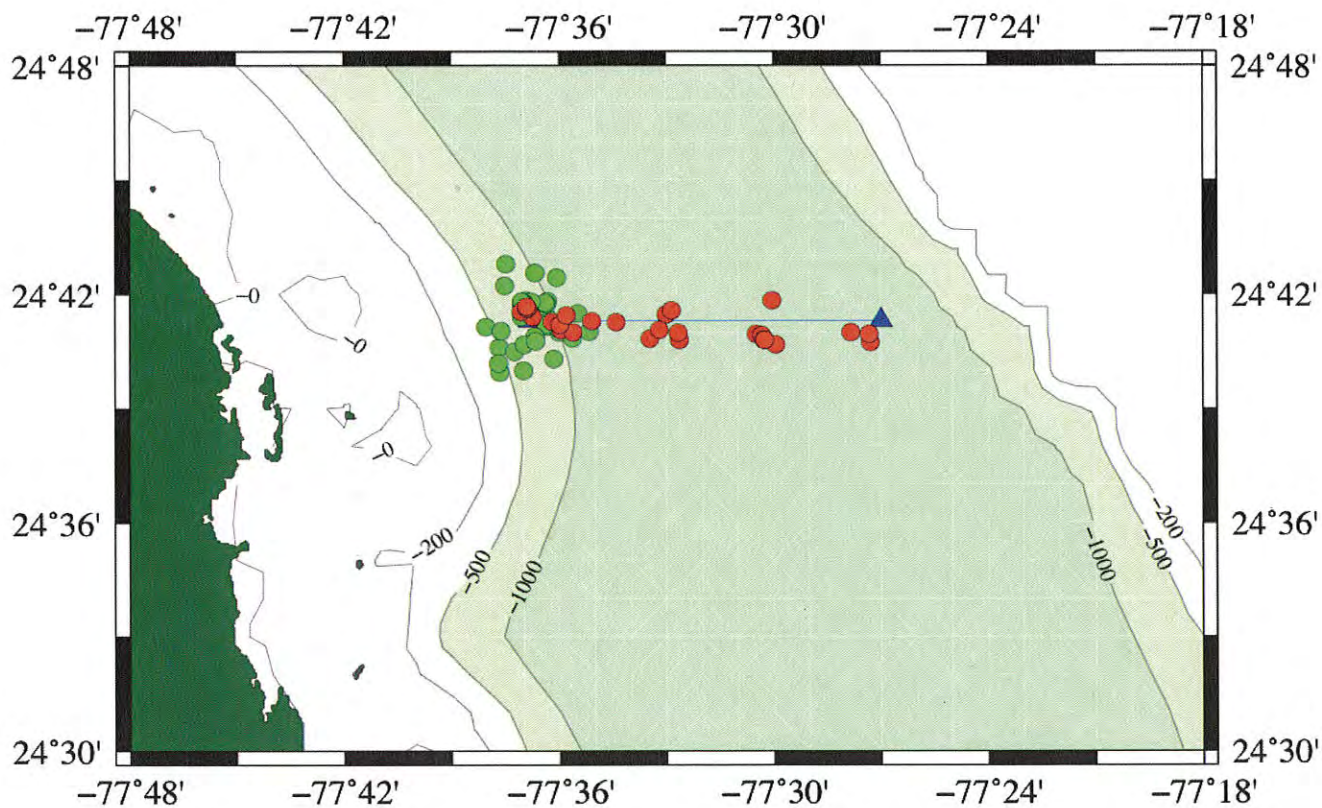


FIG. 2. Sample click of *Ziphius* click as received by the tag of a covey whale. The top panel shows the time series, the middle panel shows the spectrogram (linear spectral scale, Ham window for FFT of 32 samples, and overlap of 11 samples) and bottom panel shows the relative power spectrum.

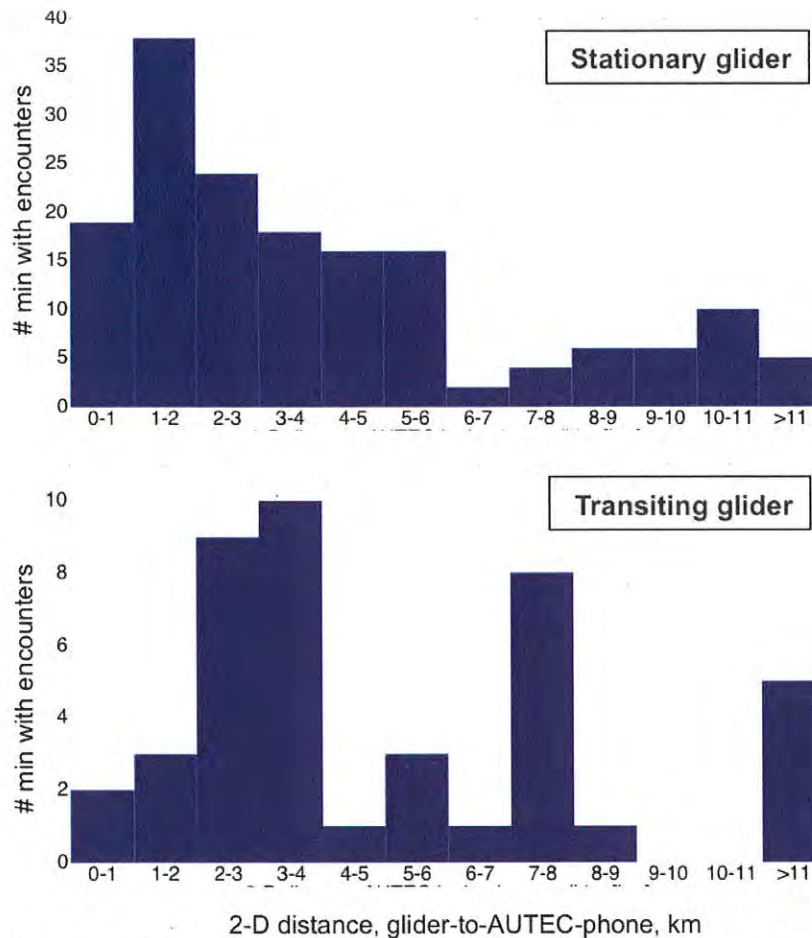
## Clicks from sg022, dive 064 (091108\_174958)



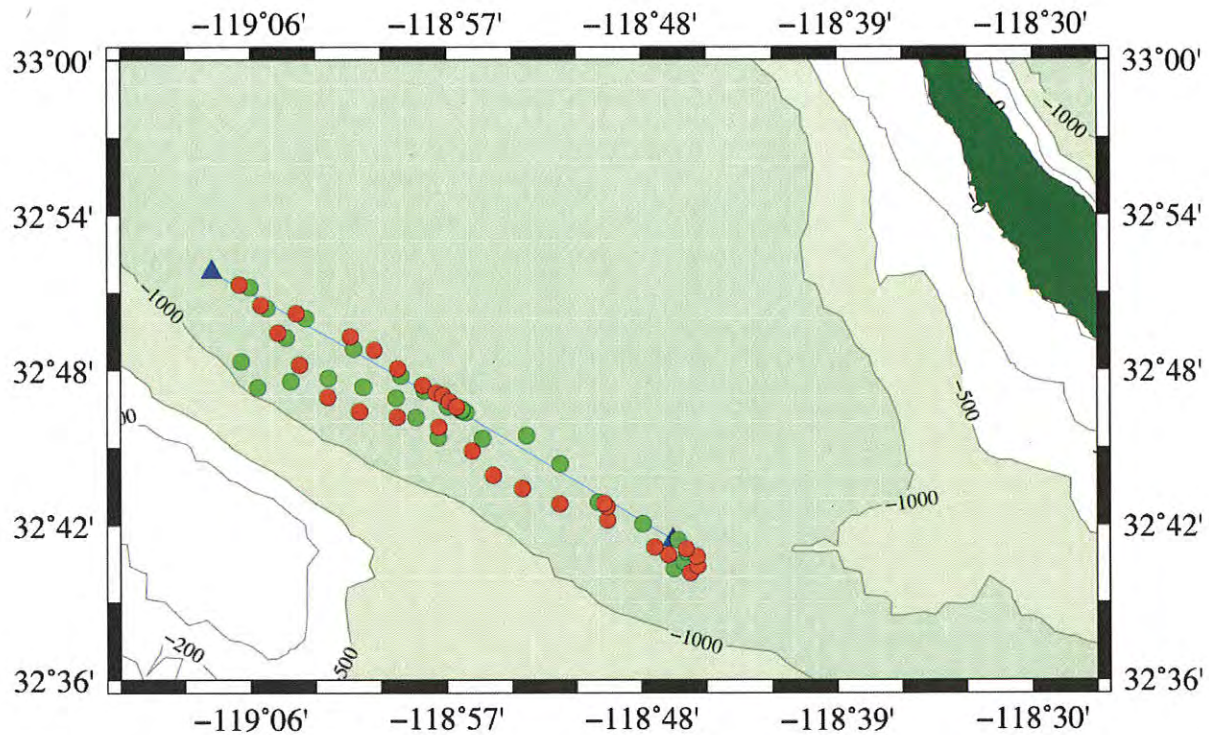
**Figure 5.** Comparison of published *Ziphius cavirostris* click (Zimmer, *et al.* [2005]) with click recorded by Seaglider/PAAM system, at 912m depth near 19°35.05'N, 156°02.45'W, on 8NOV2009.



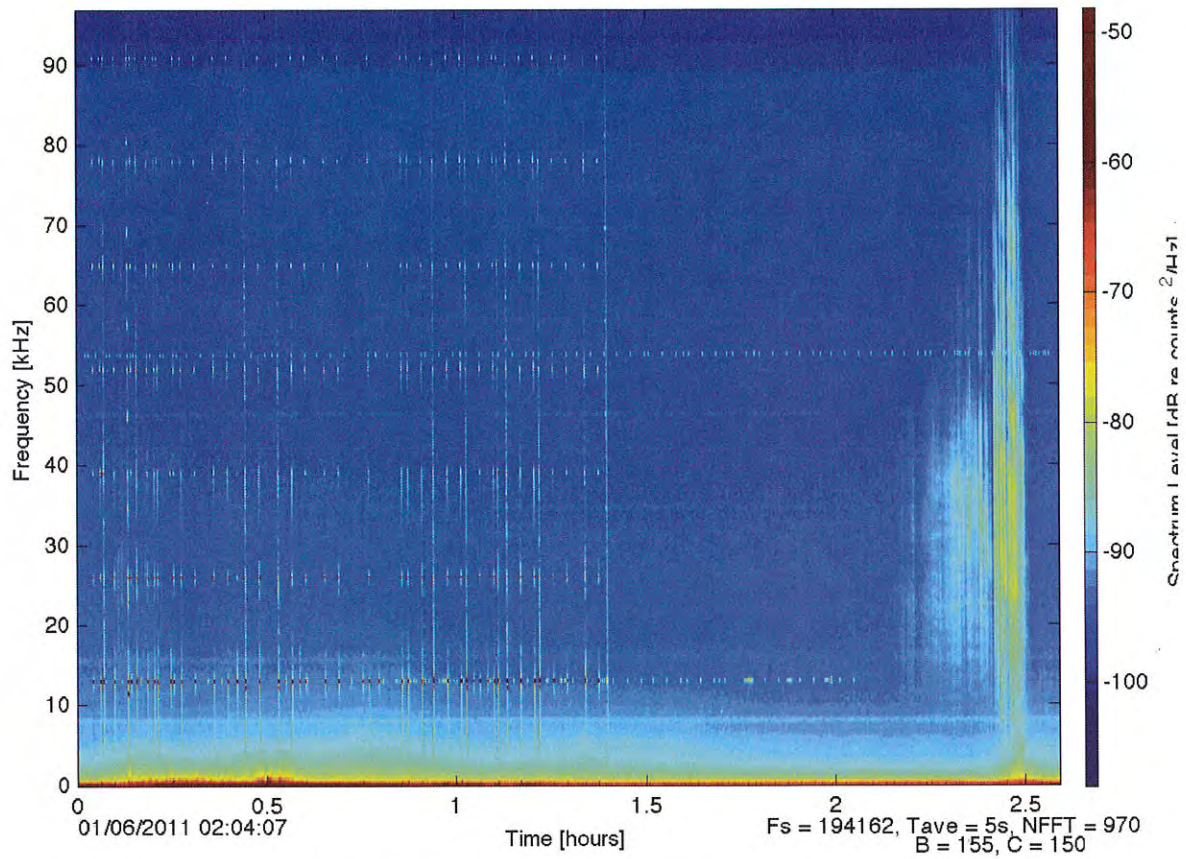
**Figure 6.** Seaglider deployment at AUTECH: 7-11JUN2010, showing SG178 (green circles) station keeping at H4, and SG179 (red circles) running east-west transects from H4 to the eastern edge of the AUTECH hydrophone array. Seaglider waypoints and intended track are shown in blue. Bathymetry (in meters) is approximate.



**Figure 7.** Plots of distance from Seaglider to the nearest AUTECH hydrophone with a beaked whale detection within 5 minutes of each other. Note that this is not the distance from the Seaglider to the beaked whale. The vertical axis in each plot is the number of minutes with a beaked whale encounter. The stationary glider (SG178) held position near AUTECH array W1; the transiting glider (SG179) made E-W transects at the same latitude as the center of W1. Detections at hydrophones greater than 6km from the Seaglider are probably coincidental. [Figure and analysis courtesy of D. Mellinger, H. Klinck, K. Klinck, OSU.]



**Figure 8.** Surfacing positions of Seaglider SG178 (green circles) and SG179 (red circles) between 407JAN2011 on the SCORE range. The Seagliders were launched near the southeast waypoint (blue triangle), and flew toward the northwest waypoint (blue triangle), roughly following the 1500m isobath, before turning to return to the launch point. Both Seagliders were recovered on 7JAN2011 about midway between the two waypoints as they were headed southeast.



**Figure 9.** Long-Term Spectral Average (LTSA) plot of acoustic data from Seaglider SG178 Dive 12, 6JAN2011, SCORE range. The pulses in the first half of the record, with fundamental frequency of about 13kHz and associated overtones are due to the Seaglider's own altimeter. Note the strong acoustic signal toward the end of the dive record, probably common dolphins. [LTSA produced using the Triton software package, courtesy of S. Wiggins, UCSD.]

REPORT DOCUMENTATION PAGE					Form Approved OMB No. 0704-0188	
<p>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to the Department of Defense, Executive Service Directorate (0704-0188). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p> <p><b>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.</b></p>						
1. REPORT DATE (DD-MM-YYYY) 30-09-2011		2. REPORT TYPE Final Report		3. DATES COVERED (From - To) 01-01-2008 - 30-06-2011		
4. TITLE AND SUBTITLE Acoustic Seaglider for Beaked Whale Detection				5a. CONTRACT NUMBER		
				5b. GRANT NUMBER N00014-08-1-0309		
				5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Bogue, Neil, M Luby, James, C				5d. PROJECT NUMBER		
				5e. TASK NUMBER		
				5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Applied Physics Laboratory University of Washington 1014 NE 40th Street Seattle, WA 98105				8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research Code 322 875 N. Randolph Street, Suite 1425 Arlington VA 22203-1995				10. SPONSOR/MONITOR'S ACRONYM(S) ONR		
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION/AVAILABILITY STATEMENT Distribution statement A: Approved for public release; distribution is unlimited						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT <p>This is the final report on the Office of Naval Research (ONR)-sponsored program entitled "Acoustic Seaglider™ for Beaked Whale Detection". This research at the Applied Physics Laboratory of the University of Washington (APL-UW) was part of the ONR Passive Autonomous Acoustic Monitoring (PAAM) of marine mammals program. Research was focused on development and operation of a passive acoustic system for the buoyancy-driven autonomous underwater vehicle Seaglider, capable of autonomous detection and classification of beaked whales. The Seaglider/PAAM system consists of a single omnidirectional hydrophone, an APL-UW designed and built electronics board, and operating software. Colleagues D. Mellinger and H. Klinck at Oregon State University developed detectors and provided scientific guidance. Four major field programs were executed, including deployments at the Navy ranges AUTEK and SCORE. Beaked whale detections ranges of up to four km were noted at AUTEK. Further development of hardware and software continues under a follow-on award from ONR.</p>						
15. SUBJECT TERMS						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	
a. REPORT	b. ABSTRACT	c. THIS PAGE			Neil M. Bogue	
U	U	U	UU	20	19b. TELEPHONE NUMBER (Include area code) 206-221-7687	